PROPAGATION MODES IN K-SPACE AND RADIATION PATTERN OF METALLIC PHOTONIC BAND GAP MATERIALS (MPBG)

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Abstract
In this paper, a method proposed by Thévenot et al. is applied to analyze the radiation pattern of a dipole which is placed inside a Metallic Photonic Band Gap material (MPBG). The coupling between the propagation modes inside the PBG and the free space modes is analyzed to obtain a good antenna performance. Finally, defect modes are studied with this method as they allow to shape the radiated beam.

1. Introduction
Photonic band gap materials are periodic structures in one, two or three dimensions composed of dielectric or metallic parts. They exhibit alternatively propagation bands and band-gaps. Their behavior depends mainly on the frequency, the wave incident angle on the material and the wave polarization.
Different techniques can characterize photonic band-gap structures. For example, the plane wave decomposition gives the energy band versus wave vector in the Brillouin zone of an infinite structure. The transfer matrix method gives the band structure and the reflection or transmission coefficient of structures with a limited number of layer but with an infinite surface.
In this study, an hybrid technique is used to characterize finite MPBG excited by a half-wavelength dipole located in the center of the structure [1]. This technique has been applied to dielectric photonic band-gap materials with success [2]. Based on the FDTD method and the Fourier transform in time and space domain, the method allows to visualize propagation modes of limited structure in the reciprocal space (or wave vector space). The comparison between the mode repartition in the k-space and the radiation pattern allows the evaluation of the coupling between inner modes and free space modes, which is equivalent to the energy transfer between inside and outside the PBG. A comparison between results obtained with a dielectric PBG and a MPBG is shown and different structures are considered with or without defects.

2. Comparison between dielectric and metallic PBG
To obtain the propagation modes, an electromagnetic simulation is computed using the FDTD method which gives the value of each electromagnetic components $(e_x, e_y, e_z, h_x, h_y, h_z)$ in a discrete time and space domain. Then, a 1D and 2D Fourier transform is applied on the different space components to obtain their values in frequency and in the reciprocal space. Finally, the product of the modulus of the magnetic and electric field is performed to visualize the energy of the propagation modes in the k-space.
In practice, the structure of MPBG is finite. This limitation has an influence on the material behavior. As the resolution in the k-space is low, an optimization can be performed to obtain the best results. This increase the calculation time. A dipole located in the middle of the structure allows to excite all the modes in the xy-plane. Therefore, the propagation modes in the xy-plane can be visualized in the case of 2D MPBG.

In figure 1, the results are shown for a PBG composed of dielectric rods - figure 1(a). The dielectric constant of these rods is 9.8, the period and diameter are respectively 3.75 mm and 1.5 mm. Figure 1(c) shows the product of the modulus of the fields integrated only inside the PBG. Figure 1(d) gives the visualization of free space modes, integration outside the structure. Results obtained outside the

structure are very similar to the far field radiation pattern - figure 1(b). Figure 2 presents one of the simulated structures composed of metallic wires - figure 2(a), the radiation pattern - figure 2(b) - and the energy repartition in k space - figure 2(c). In this case, the radiation pattern is not only well correlated with the free space modes presented in the figure 2(d) but it is also correlated with the propagation modes inside the MPBG. The wave transmission from the MPBG to the free space introduces a reduction of the values for the wave vector in the two cases (dielectric and metallic PBG).

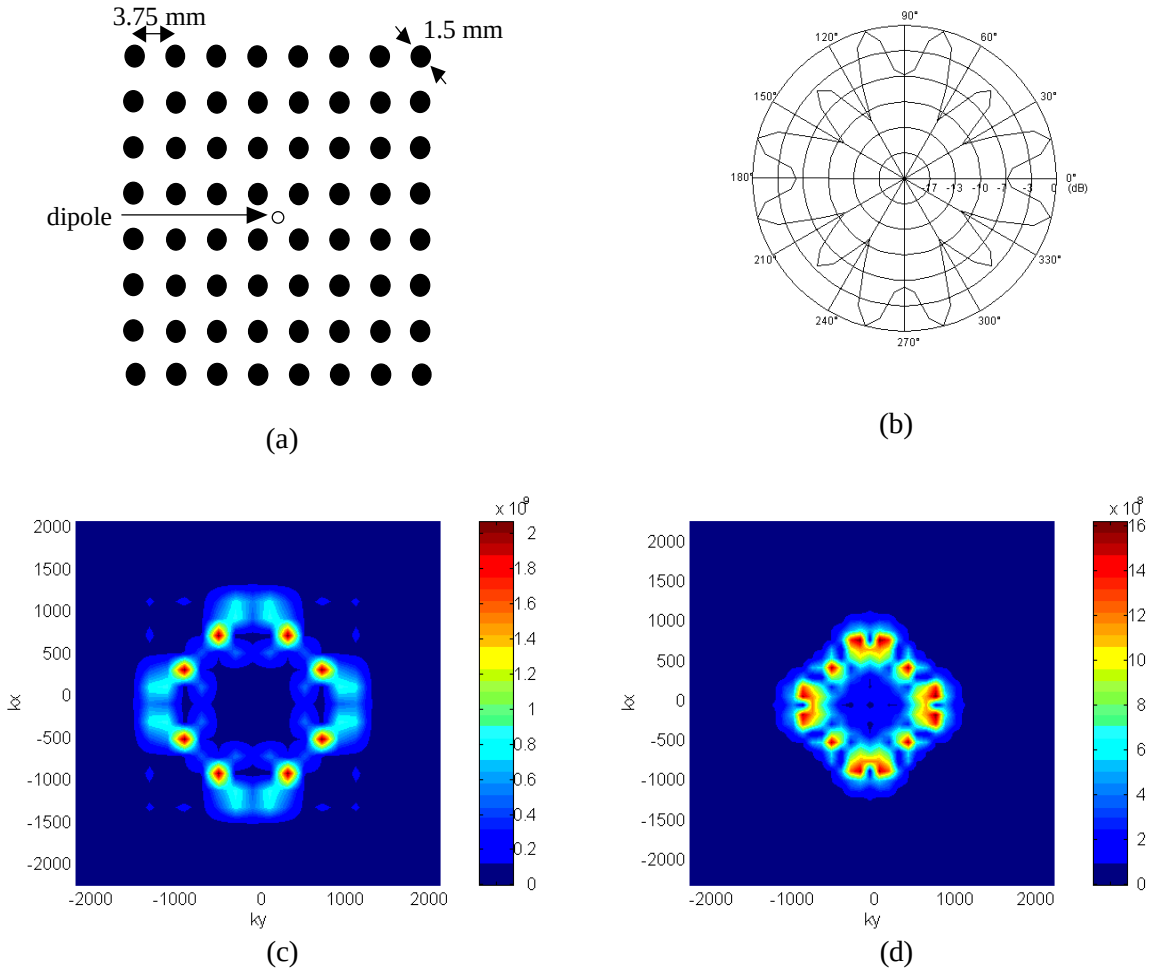

Figure 1 : Results for a dielectric PBG.
(a) Top view of the structure.
(b) Radiation pattern ($\theta = 90°$, $0 < \varphi < 360°$).
(c) propagation mode diagram of the structure.
(d) Free space mode diagram.

Figure 2 shows a good relation between the directions of the beams radiated far field and the direction of propagation of active modes inside the MPBG. The MPBG propagation modes are well coupled to the free space propagation modes. Further more, at the interface between the MPBG and free space, leaky waves and surface waves are reduced. The reduction is lower in the case of dielectric PBG. The comparison between the figure 1(c) and the figure 1(d) allows to show the creation of surface waves diffracted by the boundaries of the PBG. In the approach of metallic structures, we obtain rather an idea of the power radiated far field in propagation band than for the dielectric structures.

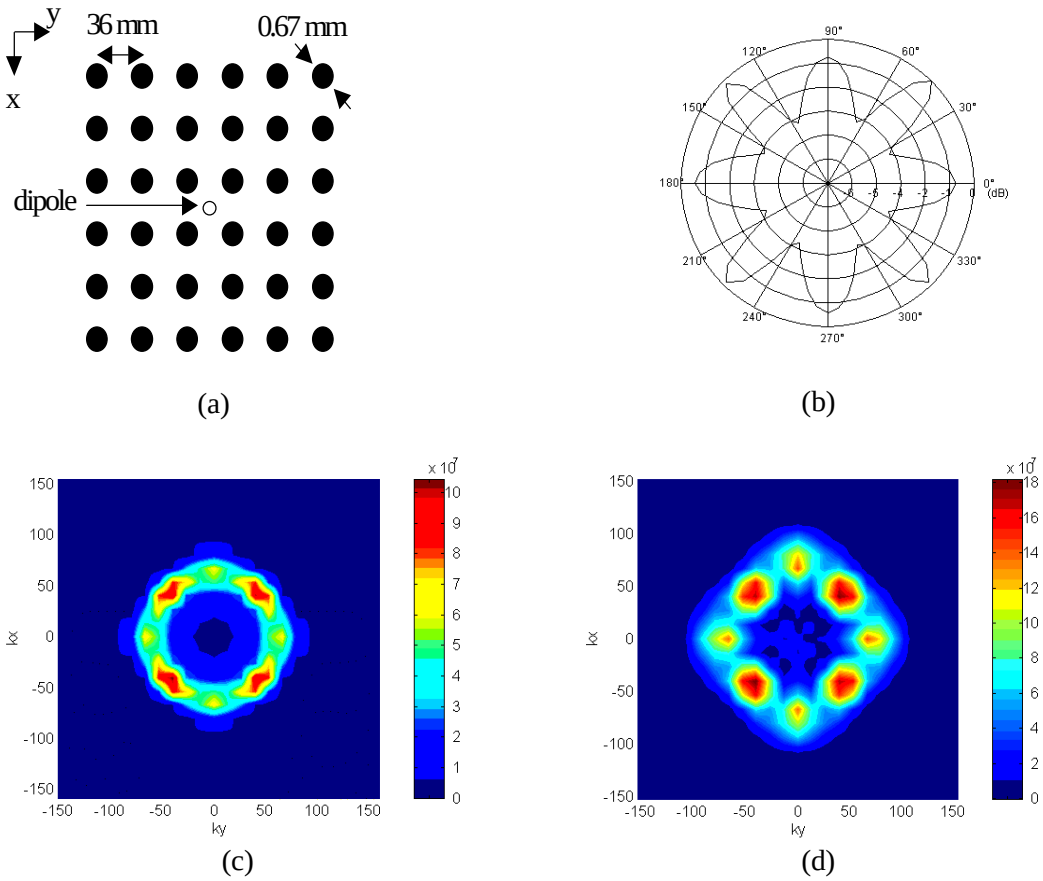

Figure 2 : Results for a metallic PBG.
(a) Top view of the structure.
(b) Radiation pattern ($\theta = 90°$, $0 < \varphi < 360°$).
(c) Propagation mode diagram of the structure.
(d) Free space mode diagram.

3. Analysis of MPBG defects

An important point is the analysis of defects in the MPBG. In fact, the localization of propagation modes in this complex structure can be difficult with the current method (plane wave decomposition, transfer matrix method). The defect introduces a dissymmetry in the crystal structure. In figure 3(a), the results are shown for a MPBG with a linear defect. This kind of defect creates a wave guide in the MPBG structure. The dipole is excited at a frequency inside the band-gap of the MPBG without defects and larger than the cut-frequency of the equivalent wave-guide. The radiation pattern is given in the figure 3(b) and with the energy distribution in the real space in the figure 3(c).

Most of the energy is radiated in the direction of the linear defect. The propagation mode diagram - figure 3(d) - is well correlated with the radiation pattern and the energy density in the xy-plane. The radiation pattern exhibits a large lobe in the direction of defect. In this case, a lot of propagation modes are excited to obtain a large lob. The mode diagram shows that a set of modes are excited due to the relatively large mode density. The mode diagram demonstrates very well the directions of propagation. This method can be performed to more complex structures like the tri-dimensional MPBG or the mixed PBG.

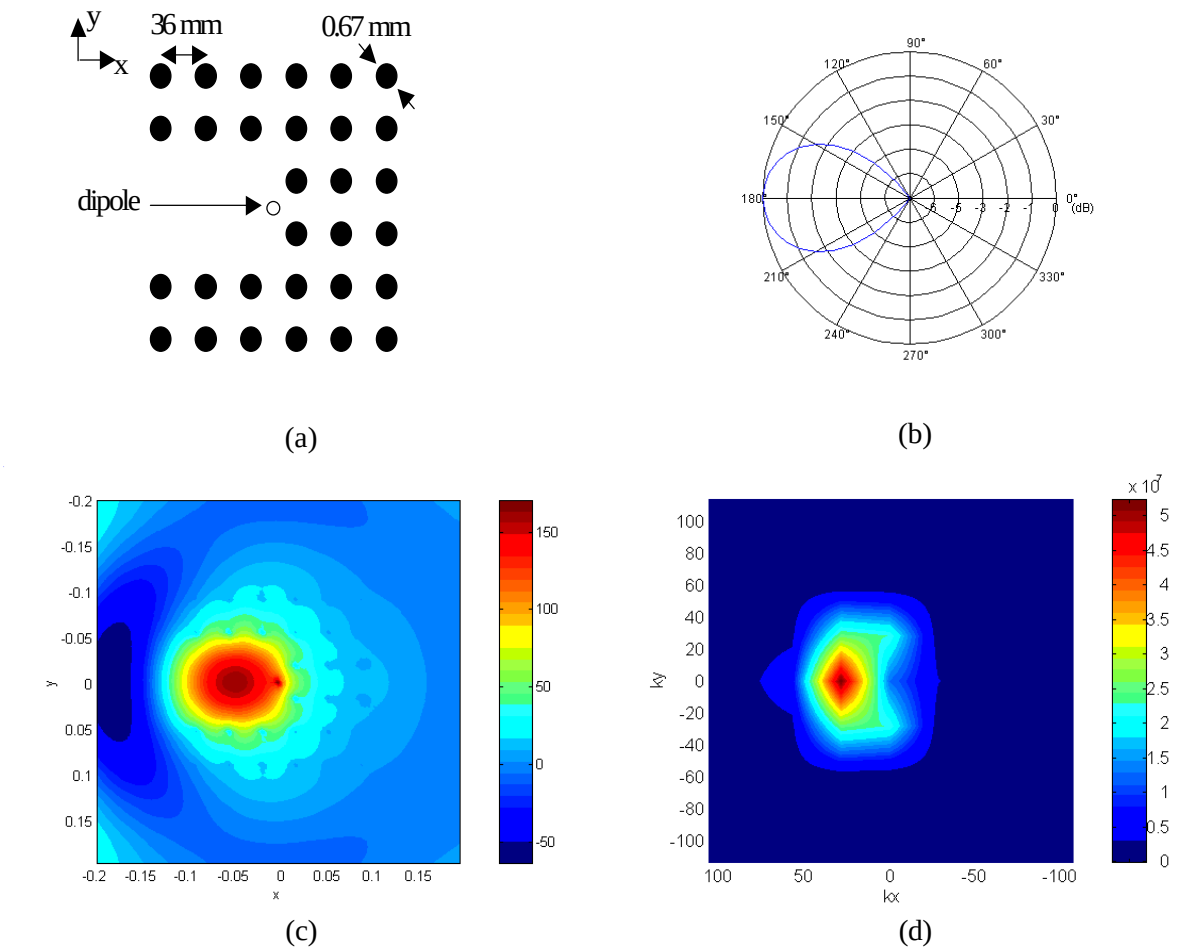

Figure 3 : Results for a metallic PBG with defects.
(a) Top view of the structure.
(b) Radiation pattern ($\theta = 90°$, $0 < \varphi < 360°$).
(c) Energy repartition in the real space.
(d) Mode diagram of the structure.

4. Conclusion

In this paper, it can be shown that with applying the numerical method (the FDTD method and the Fourier transform) on MPBG structures a good performance is obtained. The first advantage of the applied method is that the technique exhibits the reduction of surface waves by the MPBG. This reduction is important to enhance the radiated power and to obtain a better shape of the beam. The use of MPBG allows to obtain a better reduction of energy distribution in the undesirable way. Moreover, this method allows to analyze the behavior of EM waves in the complex MPBG with defects under real condition.

[1] G. Poilasne, P. Pouliguen, K. Mahdjoubi, C. Terret, Ph. Gelin and L. Desclos, “Experimental radiation pattern of dipole inside metallic photonic band-gap materials”, Microwave and Optical Technology Letters, Vol. 22, issue 1, July 1999.
[2] M. Thévenot, A. Reinex, B. Jecko, “FDTD to analyze complex PBG structures in the reciprocal space”, Microwave and Optical Technology Letters, Vol. 21, n°1, April 1999.